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Temporal Analysis of Erosion Risk Classes and Rates in the Wadi Ouergha Watershed, Northern Morocco

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ABSTRACT

The significance of the issue lies in the pivotal role played by Wadi Ouergha, as a major tributary of Wadi Sebou. This watercourse directly contributes to the El Wahda dam, the largest in the Kingdom of Morocco and the second largest in Africa. With its substantial storage capacity and noteworthy annual sedimentation volume, this dam's storage capacity is notably impacted. The ongoing decline in the capacity of the El Wahda dam could potentially accelerate due to shifts in surface water mobilization rates and the worsening degradation of marl soils within the catchment, coupled with alterations in vegetation cover. The aim of this study is to examine the changes in the erosion rate within the Wadi Ouergha watershed over a span of 40 years, covering the periods 1980–2000 and 2001–2020. This comparative analysis aims to ascertain whether erosion control measures have effectively reduced the erosion rate in the region over time. To assess soil losses occurring in the Wadi Ouergha watershed, impacting the El Wahda dam, we employed the RUSLE model to determine the rate and vulnerability of the catchment to water erosion. The results indicate that erosion control measures have been effective in combating soil erosion in the potential region with high erosion risk, with a 13.83% reduction in the average erosion rate between the two periods, from 25.3 to 21.8 (tons/hectare/year). This study presents a groundbreaking contribution by unveiling, for the first time, the dynamic evolution of water erosion patterns over time. It offers a comprehensive assessment of the effectiveness of erosion control measures implemented within the most vulnerable zones.

Keywords: Wadi Ouergha, water erosion, RUSLE, GIS, soil loss, anti-erosion practices, El Wahda dam.

INTRODUCTION

In Morocco, the most significant consequence of erosion lies in the downstream transportation of alluvial deposits generated upstream in watersheds by runoff. The mass of transported sediment ultimately accumulates in reservoirs of dams, leading to a reduction in their storage capacity. In this context, the aim of this research is to analyze the evolution of the erosion rate within the Wadi Ouergha watershed over a 40-year period, spanning from 1980 to 2020. This comparative analysis aims to ascertain whether erosion control measures have effectively reduced the erosion rate in the region over time. To assess soil losses occurring in the Wadi Ouergha watershed, which subsequently affect the El Wahda dam, we employed the Revised Universal Soil Loss Equation (RUSLE), to determine the rate and vulnerability of the catchment to water erosion. The assessment was conducted across two periods, 1980–2000 and 2001–2020, enabling the revelation of the temporal evolution of erosion risk. Wadi Ouergha constitutes a significant tributary of the Wadi Sebou; the Wadi Ouergha watershed drains 57% of the water inflows into the Sebou basin (Sebou Hydraulic Basin Agency "ABHS"). This watercourse operates under a rainy regime characterized by pronounced floods during the wet season. This circumstance has driven the construction of four dams, including the El Wahda dam, which stands as the largest dam in the kingdom of Morocco and the second largest in Africa. The El Wahda dam boasts a storage capacity of 3522.3 mm^3 (General Directorate of Hydraulics, 2020) and an annual siltation volume of 18.5 mm^3 (PDAIRE, 2011). The implications for its storage capacity approximate 10% (State Secretariat for Water, 2018). The ongoing pace of capacity decline at the El Wahda dam could potentially accelerate due to shifts in surface water mobilization rates and the worsening degradation of marl soils within the catchment, coupled with alterations in vegetation cover. In fact, erosion in the Wadi Ouergha watershed varies from one region to another depending on rainfall patterns, the prevalence of mountainous topography, the degradation of vegetation cover caused by drought and anthropogenic overexploitation. These factors, combined with the intensity of flood events, contribute to the intensification of the siltation phenomenon affecting the El Wahda dam (Department of Water, Forests, and Soil Conservation, 1995; Integrated Water Resources Management Plans, 2011). The quantification of erosion is based on the integration of erosion-related factors into the GIS, namely, the soil erodibility factor (K) determined from soil data, the topographic factor (LS) generated by the digital elevation model (DEM), the land cover, vegetation, and management factor (C) extracted from remote sensing, the erosivity of precipitation and runoff (R) calculated from climatic data, and the conservation practices factor (P) computed from data on erosion control measures implemented within the catchment.

MATERIAL AND METHODS

Study area

The study covers the watershed area of Wadi Ouergha, located within the Rif region and bounded by the following geographical coordinates: latitude 35°9' N / 34°20' N and longitude 5°49' W / 3°54' W (Figure 1). This region is known for its complex structure and high mountains of considerable altitudes. The watershed consists of a series of elongated plains within the Miocene marl basins that stretch from the Upper-Ouergha to Rharb. Wadi Ouergha meanders through their lower sections, leaving behind remnants of striking terraces, and navigates from one to another through a sudden change of direction in a narrow valley (Maurer, 1959). The relief is rugged, with elevations spanning from 11 m to 2450 m. The northern and central portions of the catchment exhibit mountains with altitudes going from 1430 m to 2450 m, while the southern and southwestern regions consist of mountains, hills, and plains with altitudes fluctuating between 11 m and 800 m.

Hydrologically, Wadi Ouergha drains an area of approximately 7300 km^2 (ABHS) with a length of 1486.5 km (Boukrim et al., 2011) and a perimeter of around 600 km. It ranks as the second major tributary of the Wadi Sebou after the Wadi Baht. Its primary tributaries are concentrated on its right bank, namely: Wadi S'ra, Wadi Amzaz, Wadi Aoulay, and Wadi Aoudour. The water contributions from its watershed amount to $2877 \cdot 10^6$ m^3/year, representing 57% of the total input to the Sebou basin (averaged over the period 1939–2002, according to ABHS).

Methodology

The rate of water erosion is influenced by four primary factors: vegetation cover, soil, topography and climate (Dwight and Smit, 1957). Soil conservation and management practices directly impact one or more of these fundamental factors, thus reducing the degree of erosion. All these factors constitute the RUSLE equation, a widely used empirical model for estimating annual soil loss within a specific area (Wischmeier and Smith, 1978). This equation can be expressed as follows (Figure 2):

$$E = LS \times C \times R \times K \times P \quad (1)$$

where: E – mean annual soil loss rate (t/ha/yr); R – rainfall erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot H^{-1} \cdot year^{-1}$); K – soil erodibility factor ($Ton \cdot h \cdot N^{-1} \cdot ha^{-1}$); LS – slope length and steepness factor (dimensionless); C – cover management factor (dimensionless); P – conservation practices factor (dimensionless).

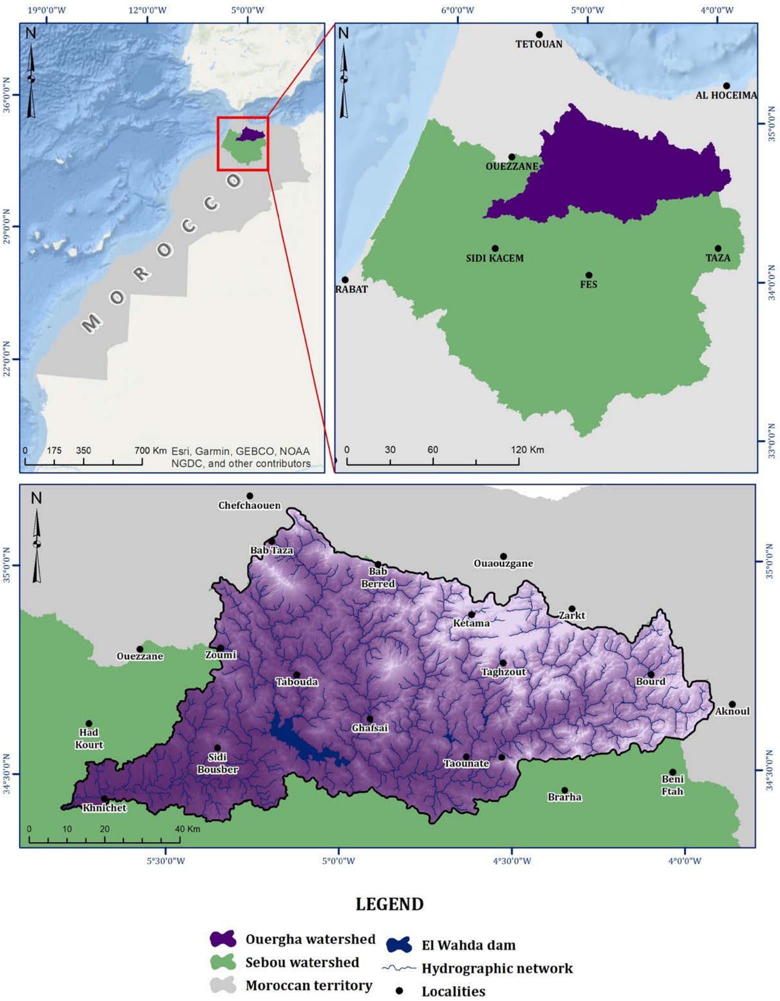

Figure 1. Wadi Ouergha watershed's geographic location

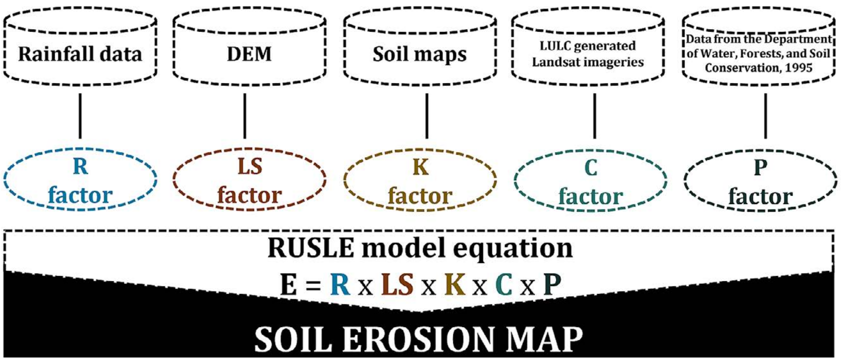

Figure 2. RUSLE model methodology

In this research, soil loss rates were computed for two time periods: 2000 and 2020. To achieve this, we prepared two databases containing all the necessary parameters to assess erosion during these two periods. However, it is important to highlight that the *LS* and *K* factors are regarded as stable over time, enabling their utilization for calculating erosion during the two periods under investigation.

Rainfall erosivity factor (R Factor)

R represents the rainfall aggressiveness or erosivity index. It corresponds to the potential erosive risks of a bare plot with a slope of 9%, where sheet erosion takes place. This index is measured in $MJ \cdot mm \cdot ha^{-1} \cdot H^{-1} \cdot year^{1}$. Building upon his research in Morocco, Arnoldus created an iso-erodent map for areas in Central Africa and the Middle East, employing the metric system (Arnoldus, 1980). The subsequent relationship was employed to develop an iso-erodent map of Morocco (Arnoldus, 1977):

$$R = 0{,}264 \times FA^{1{,}5} \tag{2}$$

with:

$$FA = \frac{\sum_{r=1}^{12} Pi^2}{P} \tag{3}$$

where: R – rainfall erosivity index (t-m·cm·ha^{-1}·H^{-1}·year^{-1}); FA – Fournier-Arnoldus index (mm); Pi – the mean monthly rainfall (mm); P – mean annual rainfall (mm).

Rainfall data was sourced from the Sebou Hydraulic Basin Agency (ABHS). To calculate R in metric units (MJ·mm·ha^{-1}·H^{-1}·yr^{-1}), the value of R is multiplied by 1.735, which is a conversion factor specifically tailored for Morocco, converting from US to metric units (Maaliou et al., 2014). The Inverse Distance Weighted (IDW) interpolation technique is used to obtain accurate values for R-factors. This method generates R-factor maps using the above equations for the given periods. This method uses an inverse weighting approach that gives greater weight to the nearest data points, and less weight to data points further away (Setianto, 2013). This allows variations in spatial data to be taken into account, while reducing the impact of outliers (Franke, Nielson, 1980).

Topographic factor (LS Factor)

LS represents the slope and gradient factor, it is dimensionless metric, which considers both the length of the slope (L) and its steepness (S). It characterizes the topographical features of the catchment. The determination of the LS factor involved the use of the subsequent equation introduced by Moore and Burch (1986).

$$LS = \left[{}^{As}/_{22{,}13}\right]^m \times \left[{}^{\sin\beta}/_{0{,}0896}\right]^n \tag{4}$$

where: As – the result of flow accumulation and cell size; B – the slope in degree; m – equals 0.4; n – equals 1.3.

The LS factor is typically computed using a Digital Elevation Model (DEM) (Wischmeier, Smith, 1978). This approach enables the determination of both the slope angle and the length of slope for every cell within the study region. These two parameters are critical for evaluating the susceptibility to soil erosion within a specific area.

Soil erodibility factor

The soil erodibility factor, denoted as K, is a comprehensive parameter that quantifies the susceptibility of soil particles to detachment caused by the force of raindrops or drainage. This factor reflects the erosion rate of different soil types, assuming all other erosion factors remain constant (Wischmeier, Smith, 1978). The identification of soil types within the Wadi Ouergha watershed area relied on two sources of data: firstly, the schematic map created by the Department of Water, Forests, and Soil Conservation during its study for the establishment of an anti-erosion development plan for Wadi Ouergha watershed area upstream of the Al Wahda dam. Secondly, the soil maps produced as part of the 1:100.000 reconnaissance study in the downstream section of the catchment, for the agricultural development of the region. The estimation of the K factor was based on data extracted from the literature (Department of Water, Forests, and Soil Conservation, 1995, Heuch 1970, Dumas 1965). The soil erodibility classification system used aligns with the framework proposed by Manrique (1988), which is similar to that of Dumas (1965) used for soils in Tunisia and the western Rif. K factor is expressed in the metric system (ton·h)/(N·ha).

Cover management factor

The cover management factor (C) is a dimensionless metric that represents the relationship between observed sheet erosion on exposed soil and erosion under a production system (García-Orenes et al., 2009; García-Orenes et al., 2010). It serves as the indicator for vegetation cover and was evaluated using satellite remote sensing data, such as Landsat 8 images for the year 2020 and Landsat 5 images for 2000. These images were subjected to supervised classification to generate a land cover map. Subsequently, this map was utilized to estimate the C factor based on scientific literature data, particularly research conducted in Morocco by Heuch in 1970, Al Karkouri in 2003 and Benzougagh in 2020. C factor values exhibit regional variations, it ranges between 0 and 1. The lowest value is linked to water bodies and gradually rises until it reaches 1 for exposed soil.

Conservation practices factor

Conservation practices factor (*P*) represents the soil conservation and management practices factor against erosion. These practices reduce the speed of runoff, subsequently reducing the rate of erosion (Wischmeier, Smith, 1978). This is explained by the fact that these practices mainly influence erosion by altering the flow, gradient, or trajectory of surface runoff, while also reducing the quantity and speed of runoff (Foster and Renard, 1983). The most important soil conservation and management practices in the Wadi Ouergha

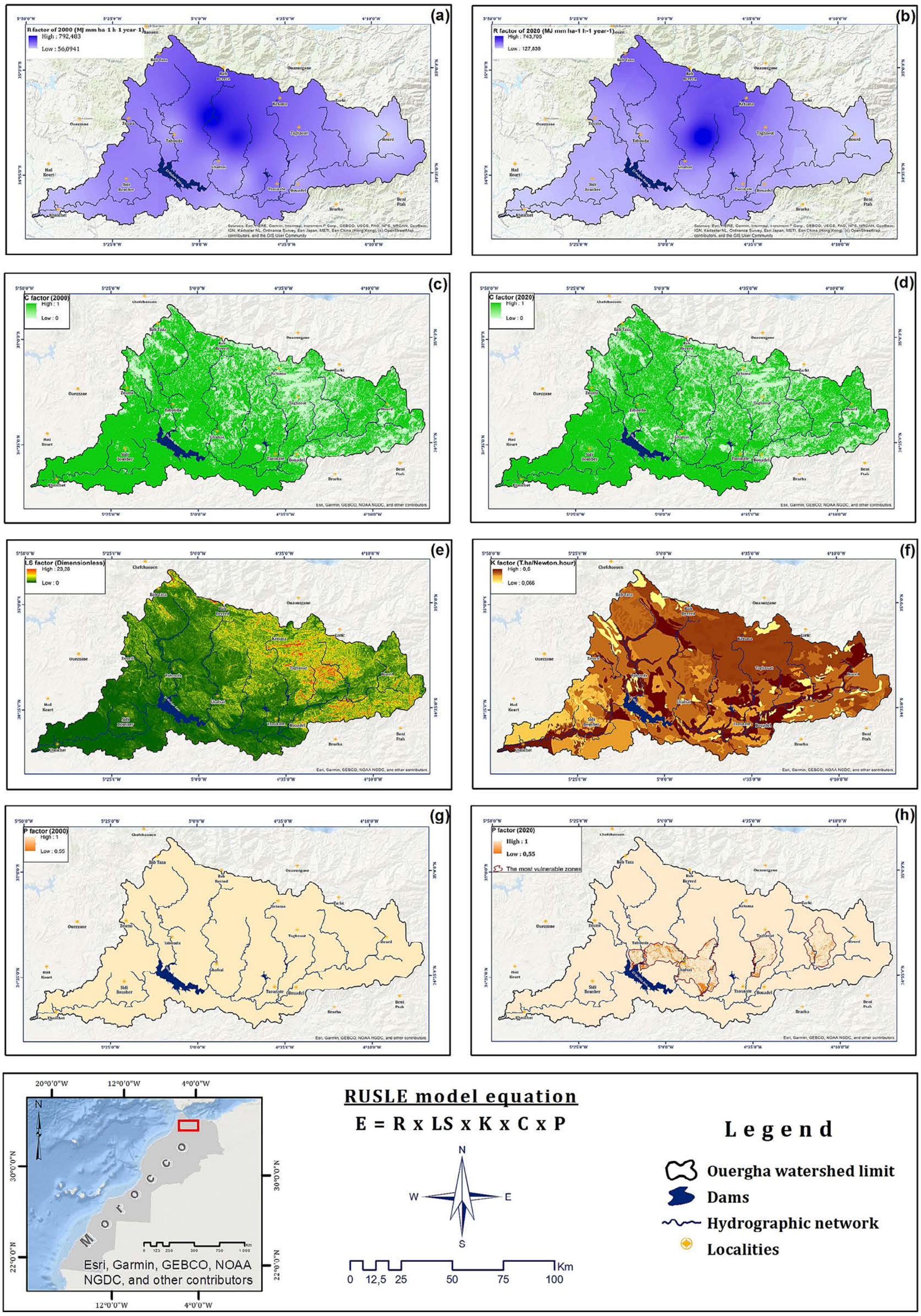

Figure 3. RUSLE input parameters' spatiotemporal allocation

watershed encompass gully rectification, bank correction, reforestation, etc. (Department of Water, Forests, and Soil Conservation, 1995). This factor's range spans from 0 to 1. The highest values correspond to areas lacking erosion control measures, while the lowest values relate to areas implementing soil conservation measures. This factor is dimensionless. The *P* factor for the entire catchment was set at a value of 1, during the initial period (1980–2000). In the subsequent period (2001–2020), specific erosion control measures were introduced, resulting in *P* factor values that vary between 0.55 and 1.

RESULTS

The results obtained using the aforementioned approach demonstrated that the R factor varied from 56 to 792.48 for the year 2000, with an average of 318, and from 127.84 to 743.7 for the year 2020, with an average of 275 (Table 1). These findings highlight a substantial variability in the R factor across the investigated time spans. Upon examining the data, it became evident that the regions with the greatest erosive potential were located in the central to northern areas of Wadi Ouergha, particularly on the mountainous terrains. Conversely, the lowest values were registered downstream of the El Wahda dam, as well as in the southwestern segment of Wadi Ouergha and the far eastern part of the catchment area. Furthermore, an examination of the meteorological data demonstrates an increase in rainfall between the periods of 1980 to 2000 and 2001 to 2020. Precipitation escalated from 694.05 mm to 764.08 mm, marking a notable rise of nearly 10%.

The LS factor for the catchment varies between 0.0024 and 23.28, indicating that 80% of the catchment area experiences a minimal contribution to erosion, in contrast to 13% which corresponds to steep slopes. The morphology of the basin is characterized by more pronounced relief in its upstream region (Figure 4). Almost one-third of its area lies at an altitude exceeding 1,000 m, while 20% spans between 600 and 1,000 m, 39% between 200 and 600 m, and less than 15% at an altitude below 200 m. The hypsometric distribution at the catchment level reveals an elevation increase from the West to the East. The surface area between two contour lines (between two classes) and the corresponding percentage of surface area were then computed. The results are presented in (Table 2).

The map illustrates a range of *K* factors varying between 0.066 and 0.6 depending on the specific soil type. The maximum value of 0.6 has been assigned to Regosols and all the complex units containing it. These formations are notably fragile and easily erodible, characterized by exposures of Upper Jurassic red clays, Upper Miocene marls and Triassic pelites. The calculated value for this unit precisely aligns with the assignment made by Heuch in 1970 to Regosols developed on poorly consolidated marl. These findings highlight that nearly all the soils within the catchment fall under the classification of highly to very highly erodible (Table 3).

By comparing the 2000 and 2020 land cover maps, it has been possible to analyze changes over time. The considered classes are water, bare land, agricultural land, woodland, sparse vegetation, and shrubland/agriculture (Table 4). Notably, concerning urban regions, it's important to acknowledge that the examined catchment area is predominantly rural, featuring scattered habitation in the form of small villages that remained undetected during satellite image analysis.

Between 2000 and 2020, significant alterations in land cover occurred. The expanse of barren land expanded notably, surging from 54.84 km² to 229.94 km², indicating a growth of 175.10 km². Similarly, the area covered by sparse vegetation experienced a substantial

Table 1. Average precipitation during the period (1980–2000; 2001–2020)

Stations	1980-2000		2001-2020	
	Average precipitation	Converage year	Moyenne precipitation	Converage year
Ain Aicha	506,75	19	519,66	20
Bab Ouender	617,25	21	695,64	20
Galez	567,19	20	717,02	20
Jbel Outka	1425,51	20	1497,32	20
Khénichet	440,53	20	485,40	20
Tabouda	607,05	20	669,43	20
Moyenne	694,05	--	764,08	--

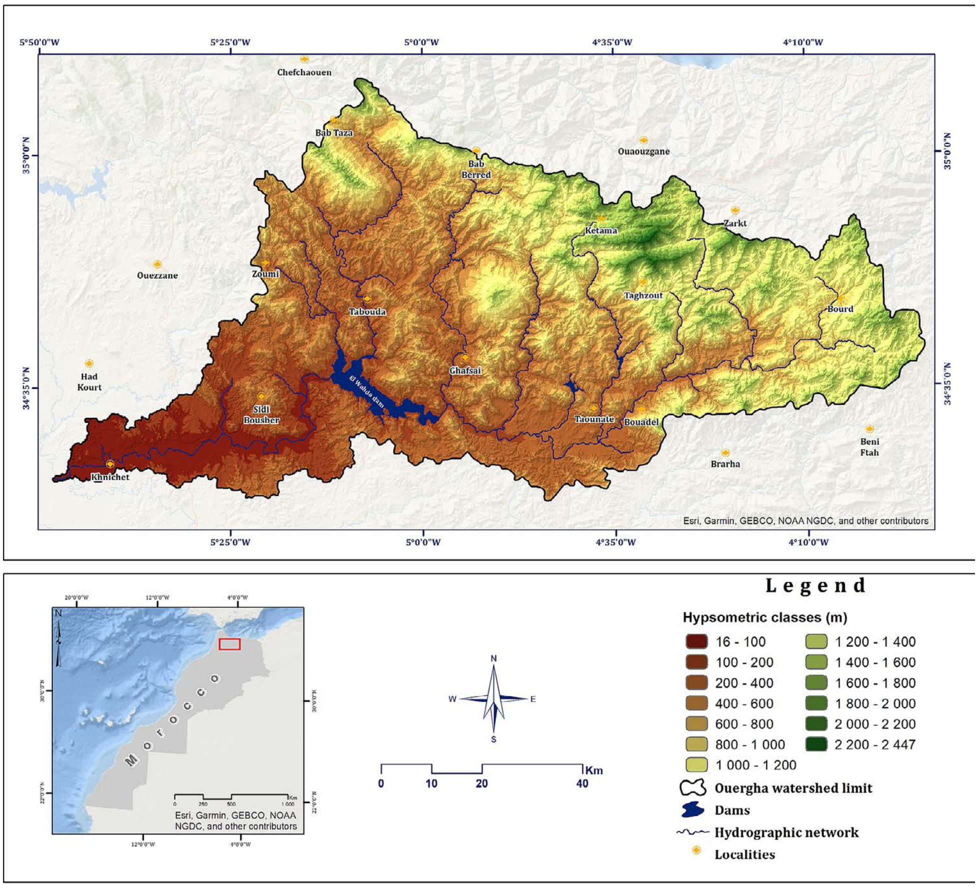

Figure 4. Map of hypsometric classes

Table 2. Hypsometric classes

Altitude classes (m)	Surfaces relatives (km^2)	% Area
16–100	402.14	5.50
100–200	645.41	8.83
200–400	1548.14	21.18
400–600	1316.37	18.01
600–800	844.30	11.55
800–1000	665.23	9.10
1000–1200	624.46	8.54
1200–1400	625.75	8.56
1400–1600	395.24	5.41
1600–1800	164.92	2.26
1800–2000	53.77	0.74
2000–2200	18.25	0.25
2200–2447	4.71	0.06
Total	7300	100.00

increase, expanding from 61.95 km^2 to 576.43 km^2, marking an augmentation of 514.48 km^2. Conversely, the area dedicated to agricultural land diminished by 391.20 km^2 over the same period, decreasing from 5105.32 km^2 to 4714.12 km^2. Furthermore, the forested area dwindled by 311.46 km^2, declining from 1747.09 km^2 to 1435.63 km^2. Lastly, minimal modifications were observed in the water and shrubland/agriculture classes between 2000 and 2020. The water area witnessed an augmentation of 31.98 km^2, whereas the area covered by shrubland/

Table 3. Soil distribution by erodibility class (after Dumas 1965 and Manrique 1988)

Risk	Classes	Relative areas (km²)	Area percentage (%)
Very low	0.066–0.15	344.20	4.80
Low	0.15–0.25	-	-
Medium	0.25–0.35	426.91	5.95
High	0.35–0.45	3162.74	44.06
Very high	0.45–0.60	3244.16	45.20

Table 4. List of land use classes

Classes	2000		2020		Evolution
	Area (km²)	Area (%)	Area (km²)	Area (%)	
Water	88.66	1.21	120.64	1.65	+31.98
Bare land	54.84	0.75	229.94	3.15	+175.10
Agricultural land	5105.32	69.30	4714.12	63.65	-391.20
Woodland	1747.09	23.91	1435.63	19.64	-311.46
Sparse vegetation	61.95	0.85	576.43	7.89	+514.48
Shrubland/agriculture	250.39	3.43	231.76	3.17	-18.64
Total	7308.25	100	7308.51	100	–

agriculture experienced a reduction of 18.64 km². By overlaying the different factors of the RUSLE equation, the soil loss map of the Wadi Ouergha watershed was generated over the two studied time frames (Figure 5). The average erosion rate exhibited a decrease of -3.5 (t/ha/yr) from 2000 to 2020, declining from 25.3 to 21.8 (t/ha/yr). This average erosion trend aligns with findings from other studies carried out in the same geographical area (Tai et al., 2021; Jaouda et al., 2018). The Table 5 illustrates a comparison of the risk of erosion within the research area between 2000 and 2020, along with the observed changes over these periods. Erosion risk is expressed in terms of erosion rate (t/ha/yr), with classes spanning from "very low" to "extremely high".

In the year 2000, a substantial portion of the catchment area (58.93%) exhibited a very low erosion risk. By 2020, this percentage had risen to encompass 62.34% of the total area. However, when examining classes associated with higher erosion risks, there is a decrease in the proportion of land area within the "high" class (from 5.58% to 5.00%) and the "very high" class (from 3.10% to 2.65%). A similar reduction is observed in the "extremely high" class (from 4.42% to 3.34%). This indicates that areas with higher susceptibility to erosion have experienced a decline over the course of the past two decades.

DISCUSSION

These results illustrate that the level of soil erosion in the Wadi Ouergha watershed is notably high, both in comparison to other areas in Morocco (Gourfi et al., 2018) and on a global scale. Recent worldwide soil erosion evaluation indicates erosion rates exceeding 20 (t/ha/yr) in the Rif mountains and High Atlas (Borrelli et al., 2017). These findings can be attributed to a combination of factors (Montgomery and Dietrich, 1994; Renard et al., 1997), including changes in land use (Table 4), climatic factors such as precipitation and drought (Table 1), as well as the topography and morphology of the catchment (Table 2). These factors often interplay in complex ways making it difficult to understand their individual effects on soil erosion in a catchment. Consequently, conducting comprehensive investigations becomes imperative to comprehend the unique influence of each factor and their cumulative repercussions on the catchment's erosion dynamics (Renard et al., 1997).

The consistent nature of the LS factor and the K factor over time, enabling simultaneous calculation, has allowed us to highlight areas most susceptible to water erosion. Typically, mountainous regions exhibit shallow soils and sparse vegetation, which can amplify runoff and erosion tendencies (Zhang et al., 2015). In contrast, downstream areas of the El Wahda dam and the southwestern segment of Wadi

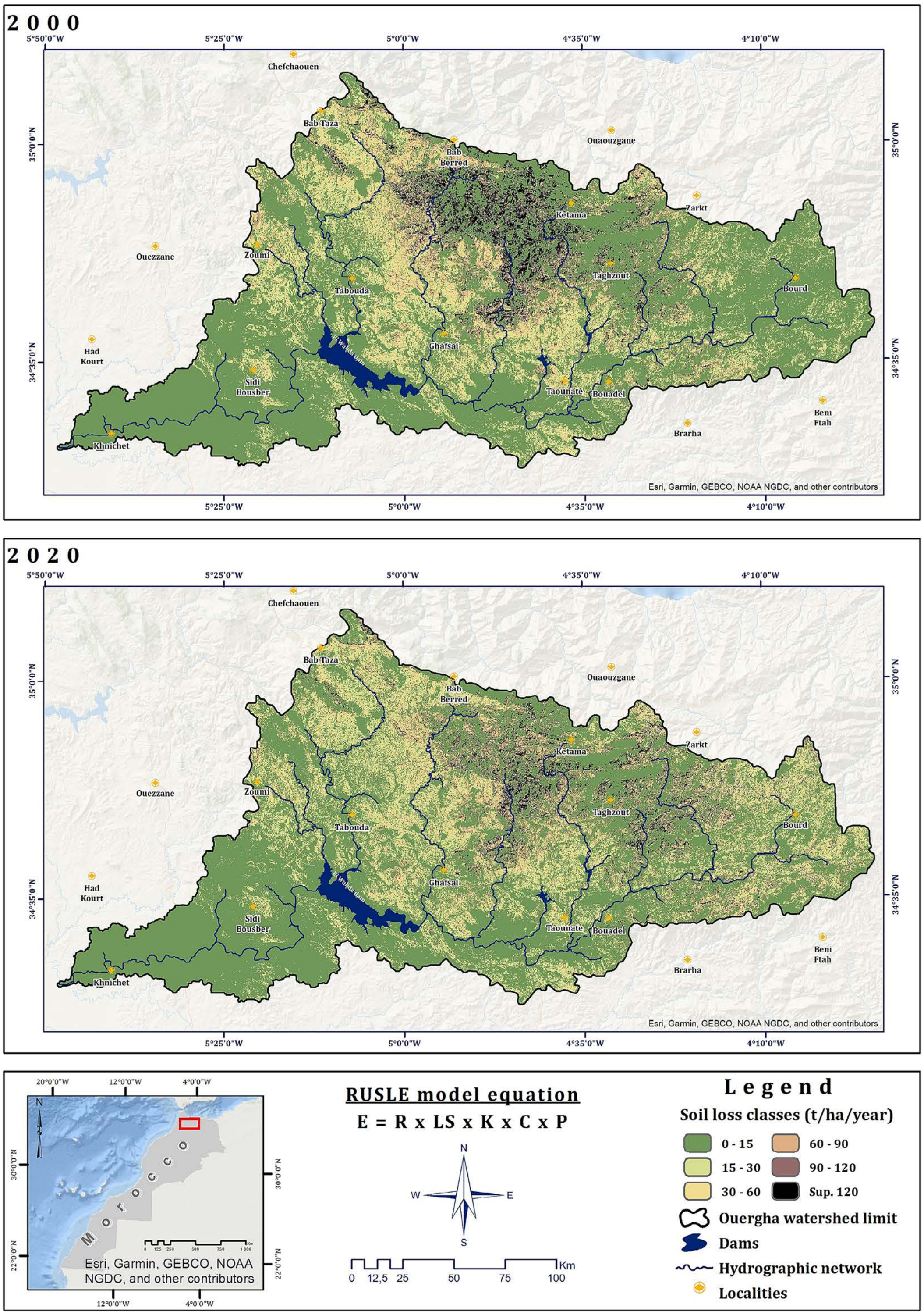

Figure 5. Maps of spatiotemporal allocation of soil loss rate within the Wadi Ouergha watershed

Ouergha exhibit deeper soils and denser vegetation cover, promoting water retention and mitigating erosion risks. These findings underscore the important role of soil management and conservation in reducing erosion within the most vulnerable zones (Figure 3h, Table 6). Importantly, this perspective should recall the conditions prevailing during the initial period.

The obtained result demonstrates an overall reduction of 16.33 km² in soil erosion rates between 2000 and 2020 within the most vulnerable zones, where soil conservation measures have been implemented. Additionally, a notable increase in the area associated with the 0–15 class of 24.25 km², representing the class with the lowest erosion rate, is observed.

Table 5. Evolution of risk classes and erosion rates (1980–2000; 2001–2020)

Risk	Classes (t/ha/year)	2000		2020		Evolution (km²)
		Area (km²)	Percentage (%)	Area (km²)	Percentage (%)	
Very low	0–15	4142.25	58.93	4332.23	62.34	+189.98
low	15–30	1012.59	14.41	978.26	14.08	-34.33
Moderate	30–60	953.50	13.56	874.89	12.59	-78.61
High	60–90	392.33	5.58	347.75	5.00	-44.58
Very high	90–120	218.17	3.10	184.08	2.65	-34.09
Extremely high	> 120	310.58	4.42	232.18	3.34	-78.40
Erosion rate (t/ha/year)	Total	998.85		1248.71		+249.86
	Moyen	25.3		21.8		-3.5

Table 6. Erosion rate within the most vulnerable zones

Risk	Classes (t/ha/year)	2000		2020		Changes (km²)
		Area (km²)	Pecentage (%)	Area (km²)	Percentage (%)	
Very low	0–15	375.42	52.99	399.67	57.75	+24.25
Low	15–30	127.89	18.05	112.84	16.30	-15.05
Moderate	30–60	122.90	17.35	103.96	15.02	-18.94
High	60–90	44.67	6.31	41.02	5.93	-3.65
Very high	90–120	20.45	2.89	18.18	2.63	-2.27
Extremly high	> 120	17.09	2.41	16.41	2.37	-0.68
Erosion rate (t/ha/year)	Total	708.41		692.08		-16.33

Conversely, a reduction is evident in the area corresponding to higher erosion rate classes, such as the 15–30 and 30–60 classes, with respective changes of 15.05 km² and 18.94 km². These findings affirm that soil conservation interventions have been particularly effective in curbing soil losses within higher-risk areas, aligning well with the outcomes of other studies (Li et al., 2011; Fowler et al., 2022; Wu et al., 2022) focusing on the efficacy of such measures.

It's important to note that the obtained results consider the influences of external factors, including climatic conditions, which can also impact soil erosion rates. Moreover, the highlighted increase in precipitation between the two periods hasn't led to a corresponding rise in erosion risk. Indeed, the intensity and duration of rainfall can influence soil erosion. Rainfall distributed over an extended period can reduce runoff and erosion (Pruski and Nearing, 2002). This could be attributed to the fact that soils have more time to absorb water, thereby reducing the amount of water available for erosion. Furthermore, to understand the impact of increased precipitation on erosion risk within the Wadi Ouergha watershed, conducting a comprehensive climatic study is imperative.

CONCLUSIONS

The widespread documentation of soil degradation caused by water erosion underscores its potential for significant socio-economic consequences, including implications such as reduced dam capacity due to sedimentation. Within the studied region, the marly composition of the soils renders them particularly susceptible to erosion risks. Their fine and friable nature make them highly susceptible to erosive forces.

This study effectively showcases the efficacy of anti-erosion measures in substantially reducing erosion rates within high-risk areas. However, it is crucial to emphasize that combating soil erosion constitutes a multifaceted challenge necessitating a comprehensive approach. Aspects including geology, climate, vegetation, topography, agricultural methods, and land use must all be taken into account to implement sustainable and effective soil conservation measures. Anti-erosion measures can only constitute a part of the solution, and other approaches such as watershed management, restoration of degraded lands, promotion of sustainable agriculture, and raising awareness among local communities are also necessary to prevent and mitigate the effects of soil erosion.

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